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正交试验方法在波形板分离器数值模拟研究中的应用

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摘 要: 为了比较精确的计算波形板惯性分离器的阻力特性,将正交试验方法与数值模拟相结合,讨论了不同数值计算方法对波形板惯性分离器阻力特性的影响,通过极差分析得出最优的数值模拟方法。研究表明: 在对惯性分离器进行数值仿真时,湍流模型对计算结果的影响最大,离散格式影响稍小,压力差补和压力速度耦合算法的影响最小; 其中,RNG $k-\varepsilon$ 湍流模型、SIMPLEC 算法、二阶压力插值、QUICK 离散格式的算法组合对波形板分离器阻力特性的预测误差为 6.8%。

关 键 词: 惯性分离器; 正交试验; 数值模拟; 实验验证
中图分类号: O357 **文献标识码**: A

引 言

进气滤清器作为燃气轮机的主要附属设备之一,可有效的降低油污、沙尘、盐分等杂质对压气机造成的性能劣化,并提高燃气轮机使用寿命[1-3]。近年来,飞速发展的计算流体力学技术使得对惯性级进气滤清器的研究逐渐从以实验研究为主的研究状况,过渡到了数值模拟与实验相结合的研究状况中。但在以往对惯性级的数值模拟研究中,往往是随机的选取一种数值模拟方法对惯性级进行气动仿真。但是由于惯性级进气滤清器主要是靠空气中液体或固体惯性进行分离,内部流场十分复杂。其数值模拟结果往往会受不同的湍流模型及计算方法等因素影响。因此找到一种计算该类流场的可靠的数值模拟方法,对进一步的研究非常重要。

本研究以某型惯性级分离器为基础,对其进行试验研究。并对该型惯性级分离器的数值模拟方案进行正交设计,考虑各种因素组合所得计算结果与实验结果的误差,并对其结果进行极差分析,找出计算惯性级分离器阻力特性的最佳算法组合。最后,对另一结构惯性级分离器进行试验,对该算法组合进行验证。

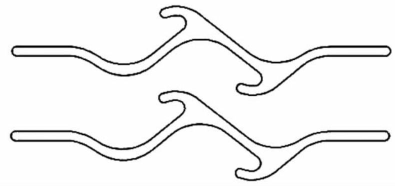

图1 惯性分离器结构简图
Fig. 1 Simplified drawing of an inertial separator

1 惯性级分离器实验研究

进气滤清器的实际工作处于常温常压状态,阻力特性的实验研究是将惯性级安装在吸入式实验风洞上,在常温常压下测量,与其实际工作状态基本吻合。实验台与惯性级实验模型如图2-图4所示。

图2 实验台前端
Fig. 2 Front end of the test rig

图3 实验台后端
Fig. 3 Back end of the test rig

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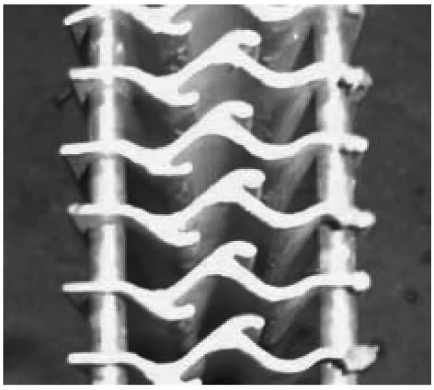

图 4　惯性分离器模型

Fig. 4 Model for the inertial separator

主要试验步骤: 将惯性级模型安装在实验风洞中，启动风机，按照事先计算出的各工况所对应的总压值调节流量阀门，记录每次测量的总压值和 U 型管压力计的水位差值，即可得到对应流速下的总压损失。

总压损失求解方法: 假设惯性级的通流面积为 A_1、进口速度为 V_1、流量管的进口面积为 A_2、流量管的速度为 V_2、则有:

$$A_1V_1 = A_2V_2 \tag{1}$$

流量管的直径为 D_2，则流量管的进口面积 A_2 为:

$$A_2 = 0.25\pi D_2^2 \tag{2}$$

而对于流量管速度 V_2 则有:

$$\rho V_2^2 = 2(P_0 - P_2) \tag{3}$$

式中: ρ —大气密度; P_0 —大气压力; P_2 —流量管处的静压。

由式(2)可以求得流量管的进口面积为 A_2，通过计算得到惯性级的通流面积为 A_1，已知惯性级的入口速度 V_1，将三者代入到式(1)中，就可以得到流量管的速度 V_2，再将 V_2 代入到式(3)中，从而得出 U 型管压力计的水位差值即($P_0 - P_2$)的值。最终通过控制流量阀的开合改变风洞内气体流速，来得到不同工况点的实验数据。最终获得的惯性级阻力特性曲线如图 5 所示。

2　惯性级数值模拟方法的正交分析

正交分析就是利用正交表，科学的安排与分析多因素实验的方法[4]。利用正交分析法可以有效的减少试验次数并能够得到每个因素对试验结果的影响情况，最终得出最优的水平组合。在本节中将使正交分析法与数值模拟有机的结合起来。将湍流模型、离散格式、差分格式和算法作为 4 种因素，并对湍流模型、差分格式、离散格式 4 种因素分别取 4 种水平，压力速度耦合算法因素取 2 种水平，利用混合正交表 L18(21×37)分析不同计算方法对惯性级分离器计算结果的影响。最终找到最适合计算惯性级分离器的阻力特性的方法。

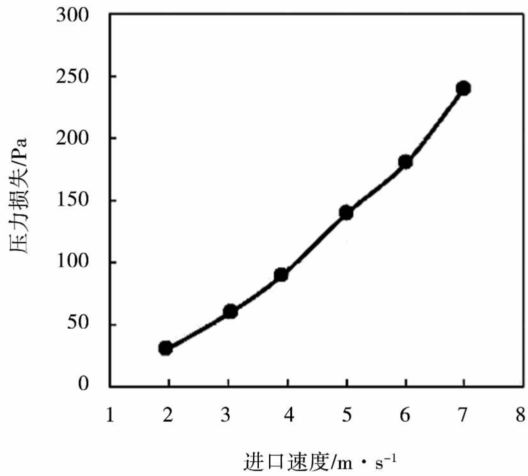

图 5　惯性分离器阻力特性曲线

Fig. 5 Resistance characteristic curves of the inertial separator

2.1　数值模拟方案

由于惯性级的高度使得上下端部对总体流动的影响相对足够小，从而某一水平断面中的二维流场可以足够精确地模拟三维实际流动。因此将以二维流动对惯性级的内部流场进行数值模拟。

进出口边界条件及固壁边界条件: 进口，速度进口，通过控制进口的流速得到不同工况点的数据; 出口，压力出口，出口总压为 0 Pa(表压); 固壁，绝热，速度满足壁面无滑移条件; 惯性分离器模型的边界采用周期性边界条件。

对模型的网格划分采用三角形网格，并在复杂边界和叶片的疏水槽部分进行了适当的局部加密。网格数量为 98079。最终计算域及网格划分如图 6 所示。

2.2　正交分析方案设计

由于 Fluent 所支持的湍流模型较多，一一试验耗时较长。因此将主要针对比较常用的 k－ε 模型

进行数值模拟。正交试验考察的因素及各因素水平如表 1 所示。

图 6　计算域网格划分

Fig. 6 Grid division of the computational domain

表 1　因素水平表

Tab. 1 Table of factors and levels

水平	A 压力速度耦合算法	B 湍流模型	C 压力插分	D 离散格式
1	SIMPLE	Standard $k-\varepsilon$	Standard	First Order Upwind
2	SIMPLEC	RNG $k-\varepsilon$	PRESTO!	Second Order Upwind
3	——	Realizable $k-\varepsilon$	Second Order	QUICK

由表 1 可以看出，该正交方案有 4 个因素，其中 A 因素压力速度耦合算法有 2 种水平，其余 3 种因素有 3 种水平，因此选择了混合正交表 $L_{18}(2^1\times3^7)$，为了能保证正交法能够得出计算精度较高的数值模拟方法，将因素 A、B、C、D 分别安排在正交表 $L_{18}(2^1\times3^7)$ 的第 1、2、3、6 列，如表 2 所示。

表 2　混合正交表 L18(21×37)

Tab. 2 Table of blended orthogonal table L18 (21×37)

方案	A	B	C	空列	空列	D	空列	空列
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

2.3　正交法数值仿真结果及分析

选取入口流速为 3.0451、5.0168 和6.9851 m/s 3 种工况下惯性级的总压损失作为表征阻力特性的参数，来进行试验值与计算值的比较，并以 3 个工况的平均误差 $\bar{\delta}$ 作为评价指标。

同时，本研究将采用极差分析法对计算结果进行分析，最终计算结果如表 3 所示。

表 3　数值模拟结果的极差分析

Tab. 3 Range analysis of the numerical simulation results

	A	B	C	D	平均误差
1	1	1	1	1	37.95%
2	1	1	2	2	35.71%
3	1	1	3	3	36.27%
4	1	2	1	2	8.27%
5	1	2	2	3	11.46%
6	1	2	3	1	18.24%
7	1	3	1	3	196.39%
8	1	3	2	1	114.57%
9	1	3	3	2	245.03%
10	2	1	1	2	37.61%
11	2	1	2	3	35.28%
12	2	1	3	1	36.94%
13	2	2	1	1	3.19%
14	2	2	2	2	10.80%
15	2	2	3	3	9.91%
16	2	3	1	3	165.61%
17	2	3	2	1	116.15%
18	2	3	3	2	186.22%
K_1	704%	220%	449%	327%	—
K_2	602%	62%	324%	524%	—
K_3	—	1024%	533%	455%	—
k_1	78%	37%	75%	55%	—
k_2	67%	10%	54%	87%	—
k_3	—	171%	89%	76%	—
R	11%	160%	35%	33%	—

表中，极差分析的统计学符号的含义为[5]：K_i—任一列上水平号为 i 时，所对应的试验结果之和；k_i—任一列上因素取水平 i 时所对应试验结果的算术平均值，s—任一列上水平 i 的试验次数，$k_i=K_i/s$；R—极差，任一列上 $R=\max\{k_1,k_2,k_3\}-\min\{k_1,k_2,k_3\}$。

通过极差分析可以看出,不同因素的极差有很大差别,由此说明不同的因素对惯性级阻力特性计算的影响程度不尽相同。通过计算结果可以看出,湍流模型对计算结果的影响是最大的,压力差值次之,而后是离散格式,影响最小的是压力速度耦合算法。

根据极差分析法,并挑选 k_1,k_2,k_3 中最小值所对应的那个水平作为较优的方案组合,较优的算法组合为 A2B2C2D1,即采用 SIMOLEC 算法,RNG $k-\varepsilon$ 湍流模型,PRESTO! 压力差补,一阶迎风离散格式的算法组合。使用该算法得出的计算结果与实验结果阻力特性曲线如图 7 所示。

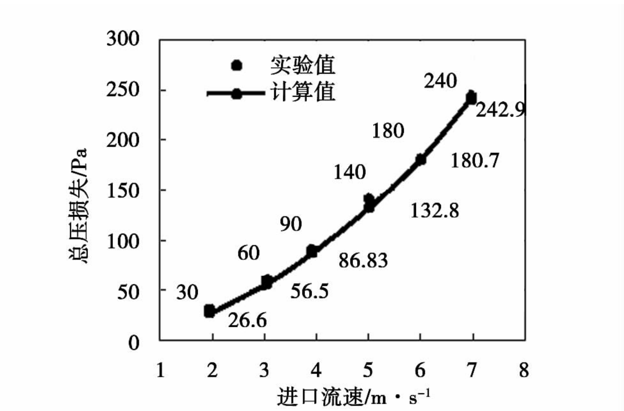

图 7　惯性分离器阻力特性曲线

Fig. 7 Curves showing the resistance characteristies of the inertial separator

计算值与实验值的平均相对误差为 4.6%。基本满足工程设计要求。

3　计算方法验证

利用相同实验台对另一结构的惯性级分离器进行试验并与采用 SIMOLEC 算法、RNG $k-\varepsilon$ 湍流模型、PRESTO! 压力差补、一阶迎风离散格式的算法组合计算出的结果对比验证。新结构惯性级分离器模型及计算域网格划分如图 8、图 9 所示。

图 8　新计算域网格划分

Fig. 8 Grid division of the new computational domain

图 10 为新结构惯性分离器试验值与数值模拟值的阻力特性曲线对比。

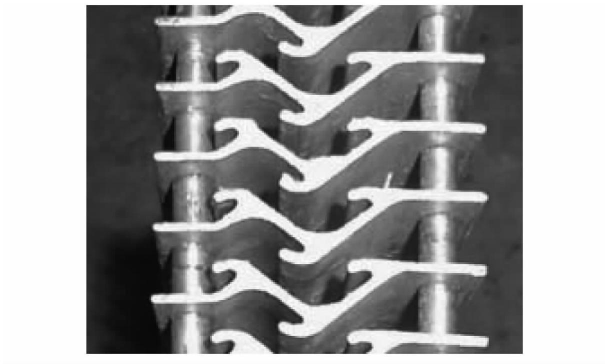

图 9　新结构惯性分离器模型

Fig. 9 Model for the inertial separator with new structures

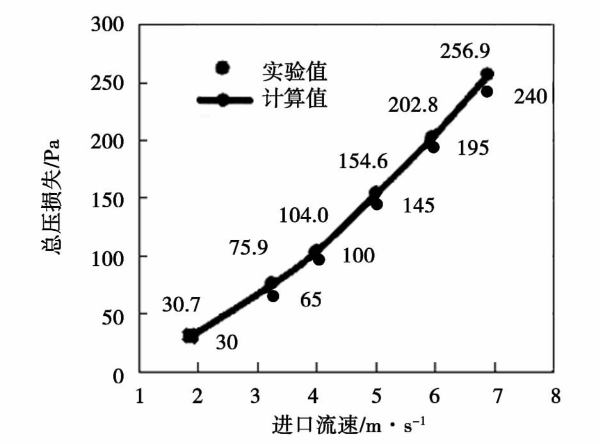

图 10　新惯性分离器阻力特性曲线对比

Fig. 10 Comparison of the new and old resistance characteristic curves of the inertial separator

由图 10 可以看出,采用第 3 节中得出的数值模拟算法计算得到的结果与实验结果基本吻合。通过计算得出计算值与试验值的平均相对误差为6.8%,基本满足工程设计要求。由此可以看出,使用该数值模拟方法计算得出的惯性级阻力特性有较高的精确度,是一种较为理想的计算方法。

4　结　论

本研究将正交法、数值模拟和实验有机的结合在一起,以较常用的 $k-\varepsilon$ 模型为基础,综合考察了多种数值模拟方法对惯性级阻力损失计算结果的影

响。并通过极差法发现湍流模型对计算结果影响最大，其次是压力差值、离散格式，对计算结果影响最小的是压力速度耦合算法。所得到的最优数值模拟方法组合为 SIMOLEC 算法、RNG $k-\varepsilon$ 湍流模型、PRESTO! 压力差补、一阶迎风离散格式。使用该方法得到的两种惯性级阻力计算的平均误差为 4.6% 和 6.8%。表明该算法对惯性级分离器的阻力特性预测有较高的精确度，为今后惯性级分离器的优化及研究提供了有效的数值仿真方法。

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（丛 敏 编辑）

新技术、新产品

汽轮机组轴承部件振动的可靠性

据《Теплоэнергетика》2013 年 2 月刊报道，俄罗斯“中央锅炉涡轮机研究所”的专家分析了这样一些因素，诸如滑动轴承的结构、轴系轴承偏心度和轴承系统的刚度降低，对汽轮机轴承部件振动可靠性的影响。基于实物滑动没承试验台以及在俄罗斯和国外现役电站上试验和测量得到的数据，完成了分析。

在选择滑动轴承的最佳结构时，必须系统地设计、在试验台上进行实物试验、保证轴承在电厂稳定地运行（液体摩擦工况，转子在滑油楔内稳定地旋转，轴承许用载荷等）。

为了保证支承轴承可以承受的载荷并保证汽轮机转子轴颈容许的循环应力量级，在不同工况下，要监控在启动过程中和底座加热后轴承相互位置的变化。

在汽轮机组设计、制造和在电厂安装的各阶段，要保证轴承部件的动力学刚度。

这些措施保证了汽轮机轴承部件在其整个寿命期间的振动可靠性。

（吉桂明 摘译）

nano-fluid working media on the migration characteristics of the heat and mass in the film evaporation zone on the capillary curved liquid surface. It has been found that increasing the superheating degree will lead to a decrease of the area of the film evaporation zone, an increase of the heat flux density on the evaporation interface and an increase of the total heat quantity exchanged in the film evaporation zone, and at the same time, however, weaken the stability of the film interface. By adding an appropriate amount of nano particles to the traditional fluid working medium, the kinematic viscosity coefficient of the nano-fluid will decrease with an increase of the volume fraction, the heat conduction coefficient will increase with an increase of the volume fraction, thus affecting its heat and mass transfer effectiveness. In the meantime, however, the stability of the evaporation interface will be weakened. A variety of nano-fluids has a conspicuous influence on the capillary curved liquid evaporation surface and the nano-fluids with a relatively low kinematic viscosity coefficient and a relatively high heat conduction coefficient can have more heat quantity be transferred. **Key Words:** capillary curved liquid surface, nano-fluid, film evaporation, heat and mass transfer

基于改进人工蜂群算法的锅炉 NO_x 排放预测优化 = Optimization of the Prediction of the NOx Emissions of a Boiler Based on an Improved Swarm Algorithm [刊,汉] NIU Pei-feng, LIU Yong-chao, ZHANG Xian-chen, ZHANG Xiang-ye (Hebei Provincial Key Laboratory on Industrial Computer-based Control Engineering, Yanshan University, Qinhuangdao, China, Post Code: 066004) //Journal of Engineering for Thermal Energy & Power. -2014, 29(4). -427-433

Studied were the problems relating to the NO_x emissions of circulating fluidized bed boilers in power plants and improved was the artificial swarm algorithm. In combination with the least square supporting vector machine, the authors established a model for the NO_x emissions of boilers and optimized the adjustable parameters of the boiler and reduced the NO_x emissions concentration. A comparison of the improved artificial swarm algorithm with the basic artificial swarm algorithm and the particle colony algorithm indicates that the model based on the improved artificial swarm algorithm can predict very well the NO_x emissions concentration and boasts a very strong identification and generalization ability, and at the same time, it also indicates that the improved artificial swarm algorithm is quick in calculation and has an edge in optimizing data. Through a simulation test, the optimized NO_x emissions concentration can obviously decrease, displaying its practical value in engineering applications. **Key Words:** boiler combustion optimization, least square supporting vector machine, NO_x emissions concentration, artificial swarm algorithm

正交试验方法在波形板分离器数值模拟研究中的应用 = Applications of the Orthogonal Test Method in the Numerical Simulation Study of Waveform Plate Separators [刊,汉] WANG Song, WANG Ting, ZHANG Zhi-qiang, WANG Meng (College of Power and Energy Source Engineering, Harbin Engineering University, Harbin, Chi-

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To comparatively precisely calculating the resistance characteristics of a waveform plate inertial separator,the authors combined the orthogonal test method with the numerical simulation. On this basis,the influence of different numerical calculation methods on the resistance characteristics of the waveform plate inertial separator was discussed and an optimum numerical simulation method was obtained through a range analysis. It has been found that when the inertial separator is numerically simulated,the turbulent flow model has a biggest influence on the calculation results,the discrete format has a slightly small influence and the pressure difference compensation and pressure-speed coupled algorithm has a smallest influence,among which the combination of RNG $k-\varepsilon$ turbulent flow model,Simplec algorithm,second-order pressure interpolation and Quick discrete model has an error of 6.8% in predicting the resistance characteristics of the waveform plate separator. **Key Words:** inertial separator,orthogonal test,numerical simulation,test verification

核电常规岛给水泵 CAP1400 **转子动力学分析 = Dynamic Analysis of the CAP** 1400 **Rotor of a Feedwater Pump in the Conventional Island of a Nuclear Power Station [刊,汉]** MIAO Fang-ming,CHEN Ning,ZHANG Jiang-tao (Shanghai Electric Power Repairing and Manufacturing Factory Co. Ltd.,Shanghai,China,Post Code: 201316) //Journal of Engineering for Thermal Energy & Power. -2014,29(4). -439-444

In the light of the problems relating to the safety and smooth operation of the CAP1400 tilting-pad sliding bearing-rotor system of a feedwater pump in the conventional island in a nuclear power station,by using the finite element QZ algorithm,calculated was the critical rotating speed under various supporting conditions. Firstly,a tilting-pad bearing with five pads were designed and such non-linear dynamic parameters of the bearing as the oil film thickness,stiffness and damping etc. were calculated. Secondly,a model for bearing-rotor systems was established and the solutions to the critical rotating speed of the tilting-pad bearing-rotor system under the rigid supporting,elastic supporting and "wet-state" supporting conditions were sought by using the characteristic data of the oil film. Finally,an on-line test was performed of the feedwater pump and the vibration values in various directions and at different locations at various flow rates were acquired. It has been found that when the oil film thickness of the tilting-pad bearing is between 0.04 mm and 0.05 mm its stiffness will increase with an increase of the rotating speed and the damping will be in this contrary. The critical rotating speed under a rigid supporting will be higher than that under the elastic supporting while an increase of the stiffness of the water film under the "wet-state" condition will make the first-order critical rotating speed be in a range from 8 100 r/min to 8 777 r/min,far higher than the actual operation rotating speed. All the vibration values and the vibration speeds of the bearing measured during the test in the vertical,horizontal and axial direction meet the national standards. The calculation result of the critical rotating speed and the test one can offer a design basis for safe and smooth operation of the tilting-pad bearing-rotor system